

# **U.S. GODAE: Global Ocean Prediction with the HYbrid Coordinate Ocean Model**

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## **LONG-TERM GOALS**

Use the HYbrid Coordinate Ocean Model (HYCOM) with data assimilation in an eddy-resolving, fully global ocean prediction system with transition to the Naval Oceanographic Office (NAVOCEANO) at .08° equatorial (~7 km mid-latitude) resolution in 2007 and .04° resolution in 2011. The model will include shallow water and provide boundary conditions to finer resolution coastal and regional models that may use HYCOM or a different model. In addition, HYCOM will be coupled to atmospheric, ice and bio-chemical models, with transition to the Fleet Numerical Meteorology and Oceanography Center (FNMOC) for the coupled ocean-atmosphere prediction.

## **OBJECTIVES**

- (1) Develop a next generation eddy-resolving, fully global ocean prediction system using HYCOM with .08° equatorial resolution.
- (2) Transition this system to NAVOCEANO for operational use in 2007 with assimilation of sea surface height (SSH) from satellite altimeters, sea surface temperature (SST) and temperature (T)/salinity (S) profiles and the ability to perform skillful 30-day forecasts.
- (3) Include two-way coupling to an ice model.
- (4) Ensure that an accurate and generalized ocean model nesting capability is in place to support regional and littoral applications, including the capability to provide boundary conditions to nested models with fixed depth z-level coordinates, terrain following coordinates, generalized coordinates (HYCOM), and unstructured grids.
- (5) To facilitate this goal, develop HYCOM into a full-featured coastal ocean model in collaboration with a partnering project.
- (6) Participate in the multinational Global Ocean Data Assimilation Experiment (GODAE) and international GODAE-related ocean prediction system intercomparison projects.

## **APPROACH**

This is a highly collaborative NOPP project with 24 partnering groups listed in the proposal. These partners are universities (with Eric Chassignet at the Florida State University as the overall lead PI), government (Navy and NOAA), industry and international. Additional partnering efforts are listed

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under related projects. The description of the approach focuses primarily on aspects performed at NRL-Stennis, many in close collaboration with project partners and partnering projects.

1. Ocean model design: HYCOM is a generalized (hybrid isopycnal/ $\sigma$ /z) coordinate ocean model. It is isopycnal in the stratified ocean, but reverts to a terrain-following ( $\sigma$ ) coordinate in shallow coastal regions, and to z-level coordinates in the surface mixed layer. The vertical coordinate is dynamic in space and time via the layered continuity equation, which allows a dynamical transition between the coordinate types. Like the Miami Isopycnic Coordinate Ocean Model (MICOM), HYCOM allows isopycnals intersecting sloping topography by allowing zero thickness layers. HYCOM was developed from MICOM using the theoretical foundation for implementing a hybrid coordinate system set forth in Bleck and Boudra (1981), Bleck and Benjamin (1993) and Bleck (2002). HYCOM was largely developed under an earlier NOPP project in a close collaboration between Rainer Bleck (Goddard Institute for Space Studies), Alan Wallcraft (NRL) and George Halliwell (University of Miami), the lead performer in each group. Alan Wallcraft is in charge of developing and maintaining the standard version of the model, one that is scalable/portable and can run on the latest computer architectures. HYCOM is maintained as a single source code with the maximum feasible backward compatibility.

2. Data assimilation techniques: Primarily, NRL-Stennis is using multi-variate optimum interpolation (MVOI) (Daley, 1991) in the NRL Coupled Ocean Data Assimilation (NCODA) system (Cummings, 2005), which was adapted for use in HYCOM in collaboration with O.M. Smedstad (Planning Systems, Inc.), C. Thacker (NOAA/AOML) and H.-S. Kang (U. Miami). 3DVAR is a planned upgrade to NCODA, which also includes advanced data QC. The primary data types are SSH from satellite altimetry, SST and subsurface T & S profiles. Either the Cooper and Haines (1996) technique or synthetic T & S profiles (Fox et al., 2002) can be used for downward projection of SSH and SST.

3. Ocean model and prediction system configurations: The primary model domain is a fully global HYCOM configuration. It consists of a bipolar Arctic grid matched to a Mercator grid at 47°N. The resolution is  $.08^\circ \cos\theta$  in latitude ( $\theta$ ) south of 47°N by  $.08^\circ$  in longitude or  $\sim 7$  km resolution for each model variable at mid-latitudes and 3.5 km at the North Pole. The array size is 4500 x 3298 with 32 hybrid layers in the vertical. The model is run with atmospheric forcing only and with data assimilation using a large FY05-07 DoD High Performance Computing (HPC) Challenge grant of computer time. A  $.08^\circ$  Gulf of Mexico HYCOM configuration is the test bed for extensive testing of the NCODA system, including different options and modifications. A wide range of data sets are available for the evaluation (Chassignet et al., 2000; Hurlbert and Hogan, 2000) and these papers discuss many climatological model-data comparisons. In addition, we have long time series of transports through the Florida Straits, sea level at tide gauges, altimetric SSH, SST, subsurface T profiles from BTs and moored buoys, and T & S profiles from ARGO floats, some data obtained routinely and some from research field programs. Bill Schmitz (Woods Hole emeritus) is a part of the evaluation effort.

4. Boundary conditions for littoral and regional models (in collaboration with project partners and related projects): At NRL it includes a nesting capability for (1) HYCOM, (2) the Navy Coastal Ocean Model (NCOM) which allows mixed z-level and terrain following coordinates, and (3) a baroclinic Discontinuous-Galerkin (DG) version of ADVanced CIRCulation (ADCIRC), the latter an unstructured grid model developed at NRL-Stennis for baroclinic coastal/estuarian applications. NCOM is also a component of NRL-Monterey's regional Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS™) (Hodur, 1997) and will be nested in HYCOM within COAMPS.

5. GODAE: The project will participate in GODAE and the related prediction system intercomparison projects, e.g. the European MERSEA. The purpose of GODAE is to help justify a permanent global ocean observing system by demonstrating useful real-time global ocean products. Consistent with this goal, real-time HYCOM prediction system output will be made available to the public within 24 hours via a 100 Tb Live Access Server (LAS) at Florida State. NRL is represented on the International GODAE Steering Team (IGST) by J. Cummings and H. Hurlburt.

## WORK COMPLETED

Two HYCOM NOPP GODAE project meetings were held in Miami in Dec. 2005 and Feb. 2006, the former after cancellation of the Aug 2005 meeting at Stennis Space Center due to Hurricane Katrina. H. Hurlburt represented the project at the Dec. 2005 IGST Meeting and gave two presentations.

The  $.08^\circ$  fully global HYCOM configuration was run with thermobaricity using a reference depth of 2000 m for potential density, i.e. in  $\sigma_2^*$  mode in the vertical. Because isopycnal models run in  $\sigma_2^*$  mode are unstable when the abyssal temperature deviates more than  $\sim 2^\circ\text{C}$  or  $\sim 4$  psu in salinity from the reference state (Hallberg, 2005), HYCOM uses a linear combination of any 2 of 3 pressure gradients calculated using 3 different reference states. HYCOM was run on 784 dedicated processors (98 nodes) on the NAVOCEANO IBM Power 4+. A typical model month of integration uses  $\sim 22$  wallclock hours and generates  $\sim 525$  Gb of uncompressed output ( $\sim 251$  Gb of compressed output). The original  $\sigma_2^*$  simulation (run in FY05) was initialized using temperature and salinity from the  $1/4^\circ$  Generalized Digital Environmental Model (GDEM3) climatology and used the vertical mixing model of Canuto et al. (2004). The remainder were initialized from a preceding experiment. Four longer and several shorter simulations were completed during FY06 and a fifth was started. The four completed simulations consisted of two pairs of climatologically-forced simulations each used to initialize an interannually-forced simulation 2003-2005 or mid 2006. In the second set of simulations two laplacian viscosity parameters were reduced and a biharmonic was doubled. The climatological wind and thermal forcing were derived from the  $1.125^\circ$  European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA15) of Gibson et al. (1997). The interannual simulations used the ECMWF 15-year mean plus 3-hourly deviations from Fleet Numerical's Navy Operational Global Atmospheric Prediction System (NOGAPS) (Rosmond et al., 2002) on a  $1^\circ$  grid for the first experiment and the  $\sim .5^\circ$  computational grid for the second one. The bulk formulae of Kara et al. (2002) were used in all of the preceding atmospheric forcing. The fifth simulation was run 1.5 years in FY06 and will continue in FY07. It uses climatological forcing based on a more recent ECMWF Re-Analysis (ERA40) (Uppala et al., 2005) with the wind speed scaled using a QuikSCAT analysis from Mark Bourassa at Florida State. It uses the newer bulk formulae of Kara et al. (2005).

NRL, PSI and NOAA/AOML jointly adapted the MVOI/NCODA system for use with the HYCOM generalized vertical coordinate and the journal article on NCODA (Cummings, 2005) is a project publication. As a new analysis variable, NCODA computes corrections to the model isopycnal layer pressures using differences between density surfaces predicted by the model and those from observations. The layer pressure analysis increments are used where HYCOM is isopycnal, while only T and S increments are used elsewhere. An incremental updating scheme was added so that a fraction of the NCODA analysis increments could be added to the HYCOM forecast variables over a given number of time steps, ranging from 1 (direct insertion) to the number of model time steps per day. The MVOI/NCODA system has been tested extensively in a nested  $.08^\circ$  Gulf of Mexico subdomain of the  $.08^\circ$  HYCOM Atlantic prediction system using both real and simulated data. SSH data along altimeter

tracks, SST and temperature profile data were assimilated using a HYCOM forecast as the first guess. The Cooper and Haines (1996) technique was used for downward projection of the SSH data. The assimilation of simulated data was rigorously verified against the control run which provided the data. So far, the assimilation experiment with real data has been verified mainly using NAVOCEANO's operational Loop Current frontal analyses based on satellite infrared imagery. The NCODA data assimilation system has been implemented into .08° global HYCOM and initial experiments have been performed using real altimeter SSH, SST and T profiles. At present, the NCODA analysis is split into 12 overlapping regions covering the Mercator part of the model grid (66°S-47°N).

To provide an ocean nesting capability for COAMPSTM, NRL-Stennis and NRL-Monterey are collaborating to nest both HYCOM and NCOM in .08° global HYCOM. The test bed is a region off the U.S. west coast and uses non-assimilative .08° global HYCOM for initial and boundary conditions, but data-assimilative results are needed from HYCOM. Data assimilation is included in nested NCOM simulations. In nesting, NCOM uses boundary fluxes only at grid points on the model boundaries, but this is being replaced by relaxation over a buffer zone as in HYCOM, so far implemented and tested only for temperature and salinity (velocity components to be added). The .08° and .04° nested versions of HYCOM that have been developed include coupling to the 9-component biological model (COSINE). A 3D-Generalized Mapper (3DGM) was developed that allows "any to any" regridding of vertical and horizontal grids regardless of grid structure. It was used to demonstrate the capability to run NCOM with HYCOM boundary conditions.

## RESULTS

Evaluation of ocean model simulations without data assimilation is essential because ocean model simulation skill is critical to dynamical interpolation skill in ocean data assimilation and to model forecast skill, the latter lasting ~1 month for mesoscale variability because it is largely a nondeterministic response to atmospheric forcing (Hurlburt et al., 2005; Chassagnet et al., 2006; Hurlburt et al., 2006; Shriver et al., 2006). In addition, ocean model simulation skill is essential in representing ocean features that are insufficiently observed (e.g., mixed layer depth and other subsurface features) and for converting atmospheric forcing and topographic/coastline constraints into oceanographic information. The figures are designed to illustrate these points.

An accurate mean SSH field is required for addition to the deviations provided by satellite altimetry. Mean SSH from an eddy-resolving global ocean model is desirable because it can represent the mean currents/SSH fronts more sharply than is presently possible from an observation-based mean, even the state-of-the-art mean of Maximenko and Niiler (2005) vs the global HYCOM mean (Fig. 1). However, simulating a sufficiently accurate mean SSH from ocean models is extremely challenging and corrections for biases and errors in the position and strength of mean currents are required. Overall, the agreement between the .08° global HYCOM and the .5° Maximenko and Niiler (2005) mean SSH is remarkably good and the standard deviation of the difference is only 9 cm. The atmospheric forcing is a significant source of error in the model mean, e.g. the obvious difference in the South Pacific is a longstanding problem where the ECMWF forcing drives a South Equatorial Countercurrent (SECC) that is too strong (Metzger et al., 1992). In the North Atlantic it drives a western boundary current that is too weak; hence the effort to correct the ECMWF wind speed using QwikScat data and the new simulation driven by the corrected product. The modified viscosity parameters gave only modest improvement in the .08° global HYCOM simulations, but based on evaluations of the global and

several .08° Atlantic HYCOM simulations (in collaboration with Bill Schmitz), the revised values are nearly optimal and are used in the new simulation.

Figure 2 compares SSH variability from a climatologically-forced HYCOM simulation and satellite altimetry. Because of the climatological forcing, interannual SSH variability, most notably due to El Niños in the Equatorial Pacific, is missing in HYCOM. Where the variability is mainly seasonal or due to mesoscale flow instabilities, regions of high and low variability generally agree well, especially in the Antarctic Circumpolar Current region. The eastward penetration of high variability in the Gulf Stream and the Kuroshio is insufficient, as expected at this resolution. The corrected (generally stronger) wind forcing should improve it, but .04° resolution is needed for satisfactory results (Hurlburt and Hogan, 2000; Shriver et al., 2006). The dual pathway of the Kuroshio past Luzon Strait has been difficult for models to simulate (Metzger and Hurlburt, 2001). Figure 3 shows that .08° global HYCOM can simulate the longitude of the two branches, the existence of a subsurface velocity maximum and the vertical structure in the upper 300 m, although the mean currents are slightly weak. Figures 4 and 5 are model-data comparisons for an interannual HYCOM simulation. Figure 4 shows generally good statistical comparisons for 126 coastal and island tide gauge stations during 2003. In the coastal and equatorial waveguides, the nontidal sea level variations are a highly deterministic response to the atmospheric forcing, less so at island stations outside a waveguide. In Figure 5, daily SST time series from .08° global HYCOM are compared with Gulf of Mexico buoy data during Aug.-Sept. 2005 and show realistic model response to the passage of Hurricanes Katrina and Rita.

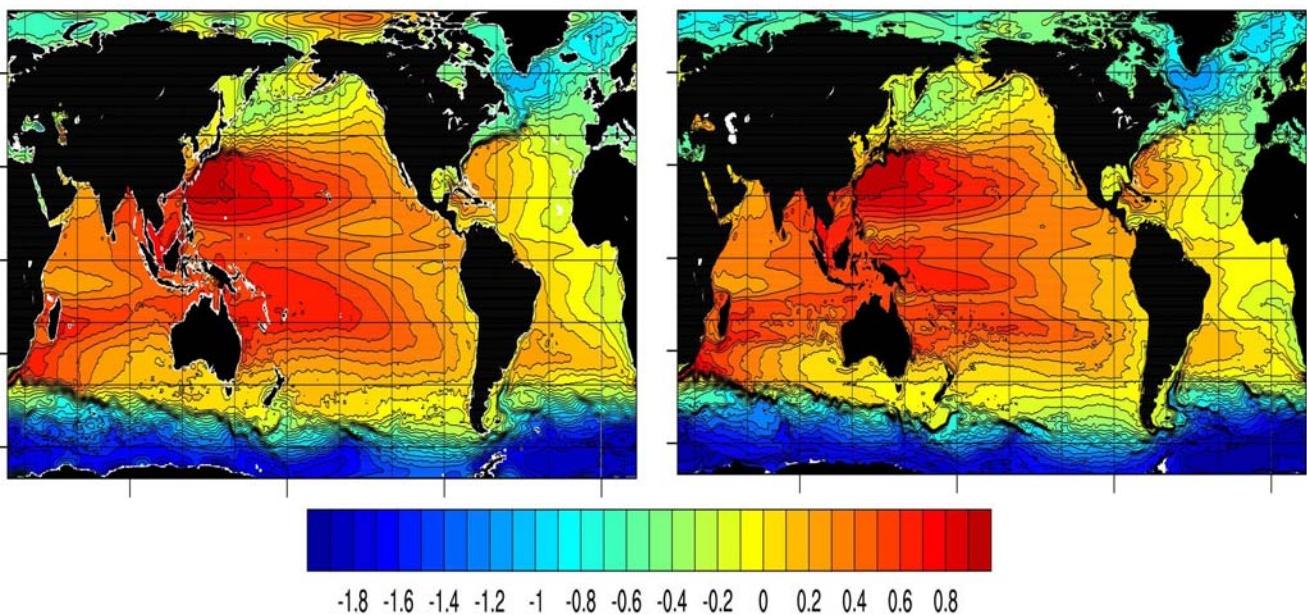
Evaluations of assimilation of simulated data in the Gulf of Mexico via NCODA show convergence to the simulated data within a month and good quantitative agreement for SSH, SST, and profiles of T, S, and velocity, even though no subsurface or current data were assimilated. Assimilation of real data, including T profiles, in Gulf of Mexico and global HYCOM generally gives good agreement with NAVOCEANO SST frontal analyses, but a better global mean SSH field is needed for use with NCODA. The present mean is not adequate to give a realistic Gulf Stream and Kuroshio as demonstrated by the short experiments run so far. Work to improve the mean is underway.

During FY06 the NRL nesting effort focused on the Gulf of Mexico (for data assimilation) and the California Current System (CCS). In the CCS region .08° global HYCOM and .08° Pacific HYCOM were evaluated along the US west coast. The unrealistically warm upper ocean thermal structure in Pacific HYCOM is much improved in global HYCOM and thus global HYCOM will be suitable in providing boundary and initial values for the west coast HYCOM and NCOM models, whereas the Pacific HYCOM was deemed unsuitable for such use. Data-assimilative results from .08° global HYCOM are needed as boundary and initial values for both HYCOM and NCOM runs in order to fully evaluate global HYCOM as a useful model for downscaling to coastal models. These results will be compared with those using global NCOM boundary and initial values.

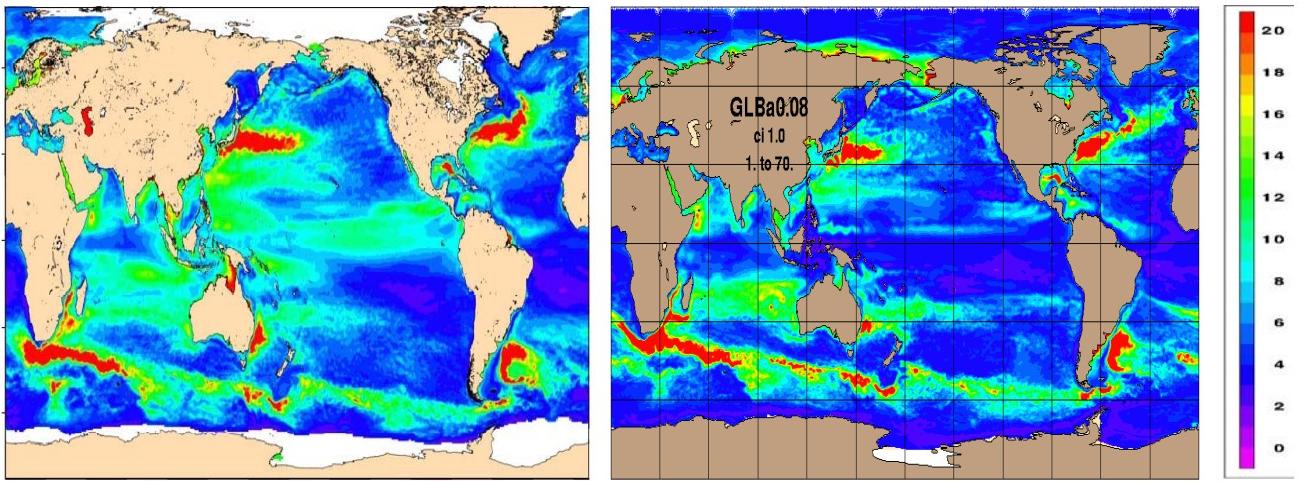
## IMPACT/APPLICATIONS

HYCOM with data assimilation is planned for use in an eddy-resolving, fully global ocean prediction system. It will provide boundary conditions to finer resolution coastal models that may use HYCOM or a different model. HYCOM is designed to make optimal use of three types of vertical coordinate, isopycnal,  $\sigma$  and z-level. Isopycnals are the natural coordinate in stratified deep water, terrain-following ( $\sigma$ ) coordinates in shallow water and z-levels within the mixed layer. The layered continuity equation allows a smooth dynamical space and time varying transition between the coordinate types.

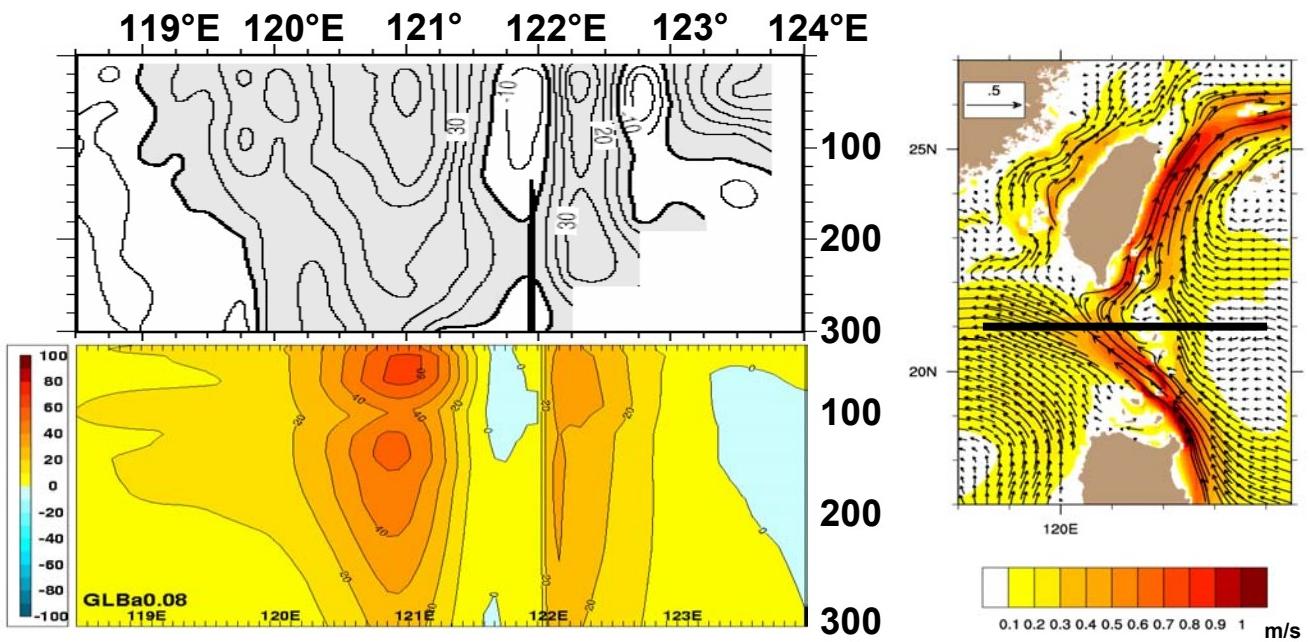
HYCOM permits isopycnals intersecting sloping topography by allowing zero thickness layers and it should allow accurate transition between deep and shallow water, historically a very difficult problem for ocean models. It also allows high vertical resolution where it is most needed, over the shelf and in the mixed layer. The isopycnal coordinate reduces the need for high vertical resolution in deep water. The project is represented by E. Chassignet (Florida State), J. Cummings (NRL) and H. Hurlburt (NRL) on the International GODAE Steering Team, a multinational effort designed to help justify a permanent global ocean observing system by demonstrating useful real-time global ocean products.



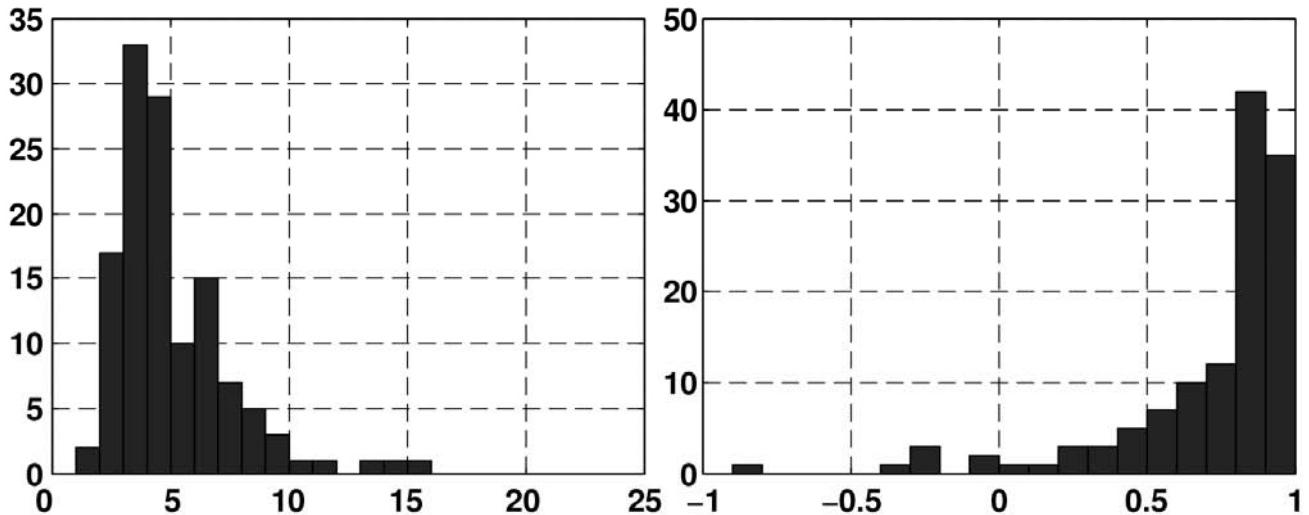
*Figure 1: Mean sea surface height (SSH) from (left) Maximenko and Niiler (2005) based on satellite altimeter, drifting buoy and wind data spanning the years 1992-2002 and a newly improved geoid, GRACE (Gravity Recovery and Climate Experiment) Gravity Model 01 (GGM01), and (right) simulated by .08° global HYCOM using ECMWF climatological wind and thermal forcing. Ten centimeters have been subtracted from the HYCOM mean.*



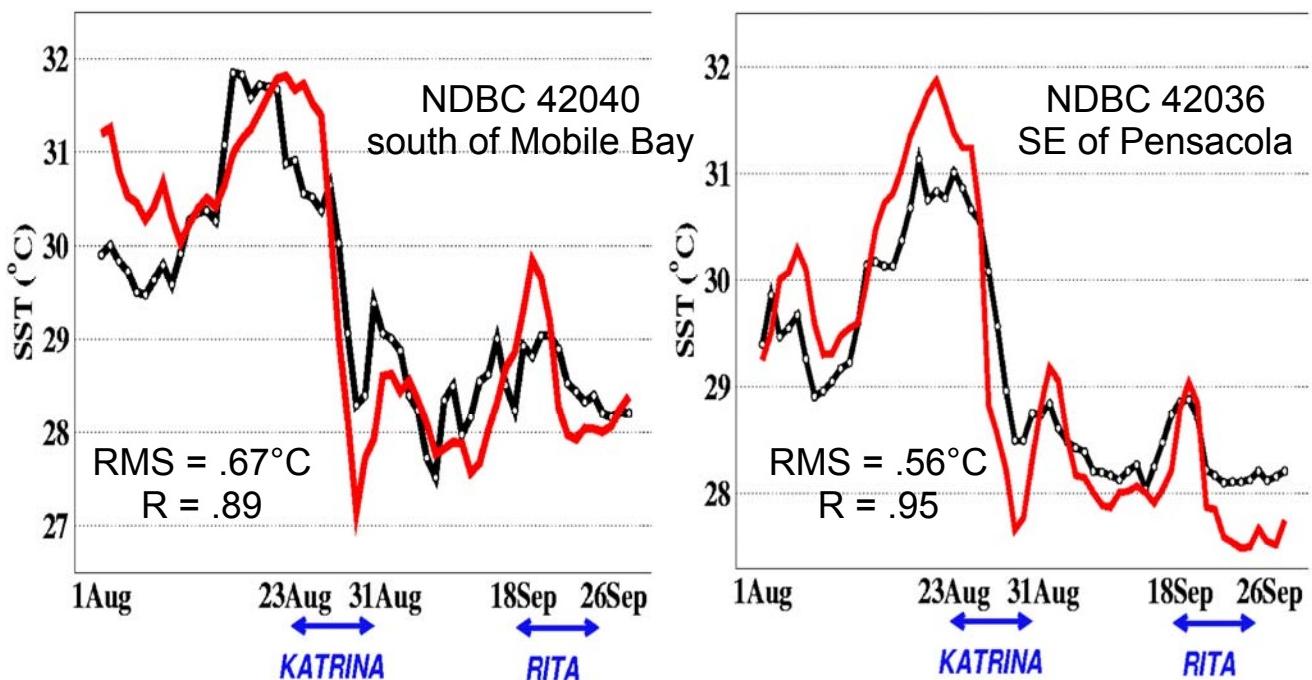
**Figure 2:** SSH variability based on (left) satellite altimeter data from Topex-Poseidon, ERS-1 and ERS-2 over the period October 1992 to May 2005 (from Collecte Localisation Satellite [CLS], France) and (right) simulated by  $.08^\circ$  global HYCOM using ECMWF climatological wind and thermal forcing.



**Figure 3:** (Right) Mean upper layer currents and their speed (in color) in Luzon Strait from  $.08^\circ$  global HYCOM using climatological wind and thermal forcing from the ECMWF. (Left – top) Mean meridional velocity in the upper 300 m based on a ten-year composite of shipboard acoustic Doppler current profiler data from Liang et al. (2003) and (left – bottom) from global HYCOM. Both observed and simulated currents indicate a split Kuroshio with a stronger western than eastern branch and weak counterflow in the lee of the Babuyan Island chain. The black line in the right panel indicates the location of the vertical cross-section.



*Figure 4: Histograms of (left) root mean square difference and (right) correlation coefficient between 126 observed coastal and island sea level stations and .08° global HYCOM using 3-hourly FNMOC NOGAPS wind and thermal forcing for 2003. A 30-day running average is applied to all time series. The median rms difference is 4.4 cm and the median correlation coefficient is .85.*



*Figure 5: Observed buoy sea surface temperature (SST) (black lines) versus .08° global HYCOM (red lines) using 3-hourly FNMOC NOGAPS wind and thermal forcing. The time series span the period of 1 August through 30 September 2005 and cover the passages of both Hurricanes Katrina and Rita. The left panel is NDBC buoy 42040 (south of Mobile Bay) and the right panel is buoy 42036 (southeast of Pensacola). Global HYCOM simulates the observed drop in SST after the passage of both storms which indicates realistic upwelling and mixing of subsurface waters as well as accurate atmospheric wind and heat flux forcing.*

## TRANSITIONS

None.

## RELATED PROJECTS

This is a highly collaborative NOPP project with 24 partnering groups listed in the proposal. These partners are universities (with Eric Chassignet at Florida State as the overall lead PI), government (Navy and NOAA), industry and international. Partnering projects at NRL include 6.1 Global Remote Littoral Forcing via Deep Water Pathways, 6.1 Air-Sea Coupling in the Coastal Zone, 6.1 Coupled physical and bio-optical processes in the Coastal Zone, 6.2 Coastal Ocean NESTing Studies (CO-NESTS), 6.2 NOPP – HYCOM Coastal Ocean Hindcasts and Predictions: Impact of Nesting in HYCOM GODAE Assimilative Hindcasts, 6.3 Battlespace Environments Institute – ESMF for Atmospheric-Ice-Ocean Coupling and Component Interoperability, 6.4 Large Scale Ocean Modeling, 6.4 Ocean Data Assimilation and 6.4 NPOESS/Mesoscale Oceanography. Additionally, the project received grants of HPC time from the DoD High Performance Computing Modernization Office, including an FY05-07 HPC challenge grant entitled “Global Ocean Prediction using HYCOM” on the IBM SP4+ at the Naval Oceanographic Office. This project is represented on the International GODAE Steering Team by E. Chassignet (Florida State), J. Cummings (NRL) and H. Hurlburt (NRL).

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